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ANALYSIS AND SYNTHESIS OF DISTRIBUTED-LUMPED-ACTIVE NETWORKS BY DIGITAL COMPUTER

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I. Introduction

The primary goal of this research grant has been an investigation of ways in which a modern digital computing facility may be applied to the analysis and synthesis of DLA networks (networks containing Distributed, Lumped and Active elements). This class of networks is of considerable importance in modern filter circuit design. One of the major reasons for this is because the fabrication techniques used to realize integrated circuits readily produce distributed, lumped, and active elements; thus, the DLA class of networks is directly realizable in integrated form. A second major reason for the importance of this class of networks is that DLA networks permit the ready realization of networks with resonant characteristics of the type usually characterized as bandpass and band-elimination, without requiring the use of inductors. The resulting inductorless realizations are attractive since, in general, they are smaller, lighter, and easier to synthesize than their purely lumped RLC counterparts. A final major reason for the importance of the DLA class of networks is that the realization of many of the more commonly required network functions can be made using considerably fewer components than would be required for a purely lumped realization, or for a lumped and active realization.

The advantages of DLA networks are not realized without encountering some disadvantages. This class of networks is, in general, not amenable to analysis and synthesis by classical techniques, since it consists of elements modeled by partial differential equations (distributed elements) as well as elements modeled by ordinary differential equations and by algebraic relations (lumped and active elements). Digital computational techniques, however, may be applied to the analysis and synthesis of this class of networks with considerable success, as will be reported in the following sections of this report.

During the preceding contract year, major research efforts have been made in two general directions, namely, the analysis and the synthesis of DLA networks. In analysis, additional investigations have been made of mathematical modeling techniques which might be used to supplement or replace the lumped element network models previously used to analyze distributed networks. In synthesis, a digital computer root-locus technique has been developed which may be used to automate the preparation of design charts for the direct synthesis of DLA networks. Details of these and other research accomplishments are given in the following sections.

II. The Use of the Matrizant in the Analysis of Distributed Networks

One of the major areas of investigation during the past contract year was the use of mathematical modeling techniques involving matrizants, since such techniques may be used to represent distributed network elements. A one-dimensional RC distributed network having a resistance per unit length r(x) and a capacitance per unit length c(x) is characterized by the following first-order matrix differentiation equation

$$\frac{d}{dx}\begin{bmatrix} V(x,p) \\ I(x,p) \end{bmatrix} = -K \begin{bmatrix} V(x,p) \\ I(x,p) \end{bmatrix} \qquad (1)$$

where V(x,p) and I(x,p) are the transforms of the voltage and current existing on the line, and where K is defined as

$$K = \begin{bmatrix} 0 & r(x) \\ pc(x) & 0 \end{bmatrix} \qquad (2)$$

A general technique for solving such a matrix equation is to use an infinite series of matrices called a matrizant. In general, for a first-order matrix differential equation having the form

$$w'(y) = A(y)\, w(y) \qquad (3)$$

we may define the infinite matrix series

$$M_0^y(A) = \sum_{i=0}^{\infty} P_i(y) \tag{4}$$

where the square matrices P_i satisfy the equations

$$\begin{aligned} P_0 &= I \\ P_{i+1} &= \int_0^y A(y)\, P_i \, dy \end{aligned} \tag{5}$$

for all integer values of i from 0 to infinity. The quantity $M_0^y(A)$ is called the matrizant and it defines the solution to the first-order differential equation of (3) by the relation

$$w(y) = M_0^y(A)\ w(0) \tag{6}$$

For the case of the distributed network, using the matrix K defined in (2) the matrizant yields the transmission parameters of the distributed network. Thus, we may write an expression involving the usual two-port network variables of voltage and current as

$$\begin{bmatrix} V_1(p) \\ I_1(p) \end{bmatrix} = M_0^d(K) \begin{bmatrix} V_2(p) \\ -I_2(p) \end{bmatrix} \tag{7}$$

where d is the length of the distributed network element. A report has been submitted outlining the method in more detail and discussing the implementation of the matrizant approach by three numerical methods, namely, the Euler method, the modified Euler method, and the method of mean coefficients, for the determination matrizant for a distributed network of exponential taper.[13] A comparison is made in the report between the matrizant and the lumped element modeling methods. In general, it is shown that the lumped element approach is superior both in terms of accuracy and computational efficiency.

III. Other Research Efforts Concerned with the Analysis of DLA Networks

Another major research effort which has been emphasized during the past contract year has been the determination of the usefulness of digital computer techniques for making analyses of two- and three-dimensional distributed elements. Usually, the distributed RC network is assumed to have variations of resistance and capacitance in only one dimension. Thus, we usually specify $r(x)$ and $c(x)$ respectively as the resistance and capacitance per unit length of such a network. Actually, however, a distributed RC network which consists of layers of conducting, dielectric, and resistive materials may more accurately be analyzed as a two-dimensional structure. Thus, we may consider quantities having the general form $r(x,y)$ and $c(x,y)$. Such variations, however, are not only difficult to analyze but they are also difficult to fabricate in integrated form. An alternate viewpoint has been chosen for investigation under this grant. This is the more practical but equally challenging problem of imposing an arbitrary terminal configuration on a two-dimensional distributed RC structure which consist of uniform resistive and dielectric layers. A set of computer programs for accomplishing the analysis of such a distributed network element has been developed. The programs also cover the more complicated case where a resistive layer is substituted for the conducting layer of the distributed RC network. The results of this investigation will be summarized in a forthcoming report.

One of the most important research tools required in studies of the properties of DLA networks is a general analysis program which has the capability of handling a wide range of network topologies, distributed elements of various tapers, etc. Such a program, DLANET, was described in the preceding annual report for this grant.*

* Annual Report, Analysis and Synthesis of Distributed-Lumped-Active Networks by Digital Computer, Research Grant NGL-03-002-136, National Aeronautics and Space Administration, September 1, 1967 to August 31, 1968, pp. 2-6.

During the past contract year a complete report describing the operation and use of this program has been submitted.[6] In addition, a continuing effort has been made to extend the capabilities of this program. As a result a modification of the original logic has been achieved so as to permit the inclusion of differential-input active elements in the network which is being analyzed. This modification has been described in a report which has been submitted.[8]

An interesting by-product of some of the research on distributed networks which was conducted during the past contract year was the discovery of an error in the previously accepted values for the network parameters of a well-known distributed notch-producing network. The corrected values have been summarized in a paper which was recently published.[11]

IV. Use of Root Locus Techniques as a DLA Network Synthesis Tool

The preceding sections of this report have described the research efforts which have been made to generate a capability for the analysis of DLA networks. Another challenging problem area is the development of synthesis capabilities for such networks. In this and the following section of this report we will describe some of the progress which has been made in this area during the past contract year.

One of the most fruitful approaches which has yet been proposed for the synthesis of DLA networks is the development of design charts which give the values for the network elements which will realize specific dominant poles and zeros. Previously the methods for determining the points needed to construct such design charts have used the concept of matching the characteristics of the network with the characteristics of some desired transfer function at selected points along the $j\omega$ axis. During the past contract year a different approach was developed which does not require the use of such matching techniques. Instead, it uses a root locus to follow the pole position as a function of some network parameter change. When a set of such root

loci are drawn for different values of some second parameter and are superimposed on a single graph, the result is a complete design chart. The concept is quite general and may be applied to a broad range of DLA networks. To implement this technique during the past contract year, a digital computer program for the generation of root loci was developed. A particularly simple method was found which could be used to generate the loci, thus, good computer efficiency was obtained. In addition, an algorithm was developed to permit automatically maintaining a scaled interval between adjacent points defining the root locus in such a manner as to make this scaling independent of the network sensitivity to parameter variations. The program is quite general and may be applied to a wide range of transcendental function as well as the more common polymonial ones. A report describing the foot locus technique and its application to the development of a design chart for a general DLA network configuration realizing a broad range of complex conjugate pole and zero locations has been submitted.[10]

V. Other Research Efforts Concerned with the Synthesis of DLA Networks

One of the most important research tools required in making synthesis studies of DLA networks is a general optimization program which may be applied to a wide range of network problems. Such a program (GOSPEL) was described in the preceding annual report.* During the past contract year, a report describing the operation and use of this program has been prepared and submitted.[5] In addition, efforts have been made to improve the capabilities of this software package. Such an improvement was the development of a grid search optimization subprogram which can be included as part of the basic GOSPEL program. A report describing this subprogram has been submitted.[9]

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* Annual Report, Analysis and Synthesis of Distributed-Lumped-Active Networks by Digital Computer, Research Grant NGL-03-002-136, National Aeronautics and Space Administration, September 1, 1967 to August 31, 1968, pp. 6-7.

As an example of one way in which an optimization program such as GOSPEL may be applied in the synthesis of DLA networks, during the preceding contract year a new method of determining the values of the elements of a DLA network for a specified dominant pole (or zero) behavior has been developed. This is based on maximizing (or minimizing) the magnitude of the network function at specific points on the complex frequency plane. The method is referred to as complex optimization. The concept is described more fully in the preceding semi-annual report.* This technique is also described in a published paper.[7] Research efforts made during the preceding contract year have indicated that the basic idea of complex optimization may be improved by applying a constraining technique to the basic method to insure that the optimization converges to a solution point representing physically realizable sets of network parameters. A paper describing these results is currently under preparation.

VI. Future Research Plans

For the following contract year research efforts are planned in several major areas. One of these is the development of a general analysis program for an arbitrary DLA network configuration. This program will be so defined that it may be directly used in complex optimization studies. Thus, such a program will combine the features of DLANET, GOSPEL, and the constrained optimization approach. This program will have many applications as a powerful research tool in attacking fundamental problems associated with the study of DLA networks.

Another research effort is planned to develop an automated synthesis procedure for preparing design charts for DLA networks using constrained complex optimization as a basic tool. This will provide an alternate capability to that which is now

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*Semi-Annual Report, Analysis and Synthesis of Distributed-Lumped-Active Networks by Digital Computer, Research Grant NGL-03-002-136, National Aeronautics and Space Administration, September 1, 1967 to February 28, 1969. pp. 1-3.

available using the root locus automated synthesis procedure described in Sec. IV. As such it should prove a valuable supplementary tool for a broad range of problems of this type.

Finally, research has been initiated on determining the properties of several specific DLA network configurations using the tools described above. Some of these networks appear to have distinctive and interesting properties and a report describing them is planned for the near future.

VII. List of Contract Publications

A. Items Published During Other Contract Years

1. Huelsman, L. P., An Algorithm for the Lowpass to Bandpass Transformation, IEEE Transactions on Education, vol. E-11, no. 1, p. 72, March 1968.

2. Huelsman, L. P., and W. J. Kerwin, Digital Computer Analysis of Distributed-Lumped-Active Networks, IEEE Journal of Solid-State Circuits, vol. SC-3, no. 1, pp. 26-29, March 1968.

B. Items Published During This Contract Year

3. Huelsman, L. P., and S. P. Johnson, An Annotated Bibliography for Distributed RC Networks, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, 11 pages, September 1968.

4. Huelsman, L. P., and S. P. Johnson, The Modeling of Distributed RC Networks, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, No. 18, 25 pages, September 1968.

5. Huelsman, L. P., GOSPEL - A General Optimization Software Package for Electrical Network Design, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, 94 pages, September 1968.

6. Huelsman, L. P., DLANET - A Digital Computer Program for the Analysis of Distributed-Lumped-Active Networks, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, 46 pages, November 1968.

7. Huelsman, L. P., Synthesis of Distributed-Lumped-Active Networks by Complex Optimization, Proceedings of the Second Hawaii International Conference on System Sciences, pp. 167-171, January 22-24, 1969.

8. Huelsman, L. P., and M. L. Gentry, Modification of the Digital Computer Program DLANET to include the Effects of Differential Input Voltage-Controlled Voltage Sources, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, 13 pages, March 1969.

9. Huelsman, L. P., and G. R. Allgaier, A Grid Search Optimization Subroutine for use with the GOSPEL Optimization Software Package, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, 19 pages, June 1969.

10. Huelsman, L. P. and F. L. Watson, Automated Generation of Distributed-Lumped-Active Network Design Charts by Digital Computer Root-Locus Techniques, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, 43 pages, July 1969.

11. Huelsman, L. P., The Values of the Parameters of a Distributed RC Null Network, IEEE Transactions on Circuit Theory, vol. CT-16, no. 3, p. 376, August 1969.

12. Huelsman, L. P., The Distributed-Lumped-Active Network, IEEE Spectrum, vol. 8, pp. 51-58, August 1969.

13. Huelsman, L. P., and T. A. Liebert, A Comparison of Numerical Techniques for Determining the Parameters of Distributed RC Network, University of Arizona, Engineering Experiment Station Report, Prepared under Grant NGL 03-002-136, 29 pages, August 1969.